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Sustainability improvement in milling operation through improved tool design and optimized process parameters-an industrial case study

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Abstract

Current machining practice in a South-East England SME was studied over a 6 month period. This was preceded by exploratory academic research in sustainable machining and a set of short industrial observations/interviews. Preliminary machining tests conducted in the industry on Delrin, aluminium, carbon steel, stainless steel and Inconel 718 indicated more energy savings would be desirable with Inconel. New cutting tools were developed with potential to reduce energy consumption and tested on various features. The effect of using a trochoidal toolpath was also investigated. The results show that energy reduction was obtained for some of the features. Surface finish and tool wear and quality of type of chip produced were not impaired. The results have raised awareness of the potential for energy reduction in the SME and a major tool manufacturer involved in the study. The study has acted as exploration of factors important in the dissemination of sustainable machining in industry.

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Keywords: Sustainability performance improvement; sustainable machining; energy efficient tool design; dissemination of sustainability results

1. Introduction

Improvement of sustainability performance for manufacturing process now seats alongside traditional measures like cost, delivery time and quality. One of the manufacturing processes that have been investigated for such sustainability improvement, by researchers from around the world, is machining. In the USA, researchers working at MIT such as Dahmus and Gutowski [1] made some of the earliest interesting findings which showed that the energy for machining operation is a small proportion (often less than 20%) of the total energy consumed, the rest being used by auxiliary functions such as the coolant pump on the machine tool. Researchers from University of Berkeley beginning with Paul Sheng's research in the 1990s have demonstrated that it is possible to have a process planning system with environmental consideration embedded. Sheng and Srinivasan [2] developed a feature based multi-objective process planning system which considered environmental factors. A micro planning section is used to achieve the best overall performance by optimizing the process parameters. The macro planning section started with the aggregation of features obtained from the micro section, then further optimised the process by considering the interaction situations. It was reported that 4.5% of total energy consumption and 47.2% of fluid coated on chip could be saved [3]. UK researchers Rajemi et al. [4] developed equations to calculate energy consumed in dry turning operation which makes explicit the machining parameters such as feed rate, cutting velocity and tool life. This equation makes it possible to carry out an optimisation procedure which minimises the turning energy with respect to the cutting conditions. Further results were reported by Mativenga and Rajemi [5] which showed that in turning operations feed rate, cutting velocity and depth of cut can be optimised to minimise energy and cost simultaneously achieving reduction of up to 64%. Mori et al. [6] conducted a study in the industrial setting of Mori Seiki Co. Ltd, Japan for improving the energy efficiency for machine tools. The study considering drilling, end milling and face milling reported that by choosing suitable cutting speed, feed rate, depth and width of cut up to 66% power consumption for milling operation can be reduced without reduction in tool life or impairment in surface finish. Machining time could also be

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reduced with a material removal rate increase of up to 333%; Newman et al. [7] conducted experiments in which power consumption for end milling. showed that with a constant material removal rate, high feed rate and low depth of cut consumed less power than high depth of cut and low feedrate. The result shows that up to 6% of power could be saved when slotting aluminum workpiece. A general trend in the contributions of the various researchers is that higher cutting conditions resulted in lower energy consumption. There are still however wide variations in the reductions reported to be obtainable. Another observation is that most of these research findings were carried out in academic settings and often by individual research groups. In exceptions such as the contributions of Mori et al. [6], there is no indication whether the industry involved has adopted the sustainable practice. This paper is a preliminary exploration of how the issues mentioned above could be addressed.

1.1 Research questions, Research methodology and outline of the paper

The specific research question being addressed is:

What factors are significant in disseminating the results of academic sustainable machining research to industry?

The methodology does not follow any specific extant paradigm, but is based on assumptions that can be best interpreted as mixed or pluralistic, having elements of pre-positivist (in pre-Aristotelian and post-Aristotelian senses), positivist, post-positivist, interpretivist and critical realist traditions.

Results of research conducted at the university of Greenwich will be presented in section 2, followed by results obtained in attempt to disseminate the results in industry through short industrial observations and interviews (in section 3) and a more in-depth case study in industry (section 4). The research is largely exploratory using physical experimental methods, numerical experimentation, observation, informal interviewing techniques and mathematical modelling.

2. Results from sustainable machining research at the University of Greenwich

2.1 Definition, measurement and predictive models for performance measures of sustainable machining

Important performance measures have been identified such as energy consumption, energy consumption/volume removed, energy efficiency, cost for unit volume, time for unit volume, tool life and surface finish. One new definition for energy efficiency was developed with a potential to uncover inherent inefficiency that previous energy efficiency measures could not address. This definition defines energy efficiency, EE, as:

$$EE = 1/((TE/TME) + (AE/TME)) \tag{1}$$

With the definition of equation 1, it is seen that even if the Auxiliary Energy (AE) becomes zero, since the Theoretical Energy (TE) cannot be less that the Theoretical Minimum Energy (TME), the limiting energy efficiency of a machining operation would still be much less than 100%. This definition contrasts with current definition which when the auxiliary energy (AE) tends to zero, gives the impression that the energy efficiency of the machining operation could be 100%.

A method for measuring energy consumption without disrupting machining operation has been investigated through the use of a 3-phase power meter. The results from it were verified by using a force measurement system from Kistler Instruments.

A predictive model for energy consumption, E, has been obtained from machining science literature as shown in equation 2 (where V_m is machined volume, a_p: depth of cut; a_e: width of cut; d:diameter of end mill; z:number of teeth; f:feed rate; n:spindle speed; c_0-c_6 are constants depending on material being machined) which has been shown to have close to 90% accuracy when compared to experimental results.

$$\mathbf{E} = (2\pi V_m \cdot C_0 \cdot a_p^{C_1} \cdot a_e^{C_2} \cdot d^{C_3} \cdot z^{C_4} \cdot f^{C_5} \cdot n^{C_6})/(10^3 . z) \tag{2}$$

The values predicted by the result is shown below in figure 2 for Specific Energy Consumption (SPE) at different Material Removal Rate (MRR) along with other results in the literature for different materials. This shows similar trends and that the model in equation 2 can be generalised to different materials and different machine tool conditions. Similar models for cost, time, surface finish, tool life have also been developed.

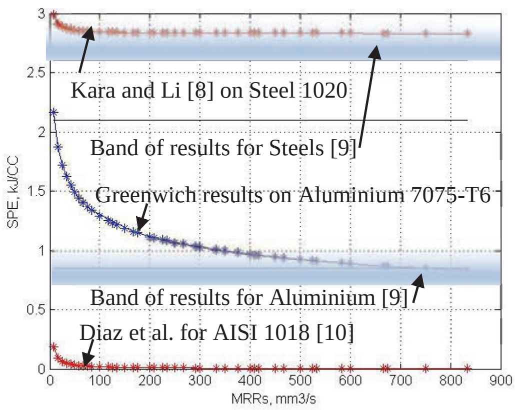

Fig. 1. Specific Energy Consumption (SPE) at different Material Removal Rate (MRR)

2.2 Analysis or characterization of factors and performance measures of sustainable machining

The predictive models for energy, cost, time, and surface finish have been characterized and shows the relationship in figure 2, indicating that energy consumption, cost and time all decrease with increase in the cutting conditions. It was also identified that for minimising energy, feed rate was found to have the most significant effect, followed by depth of cut, then spindle speed and lastly width of cut. This is similar to results obtained by Newman et al [7] who reported that high feed rate and low depth of cut consumed less power than high depth of cut and low feed rate.

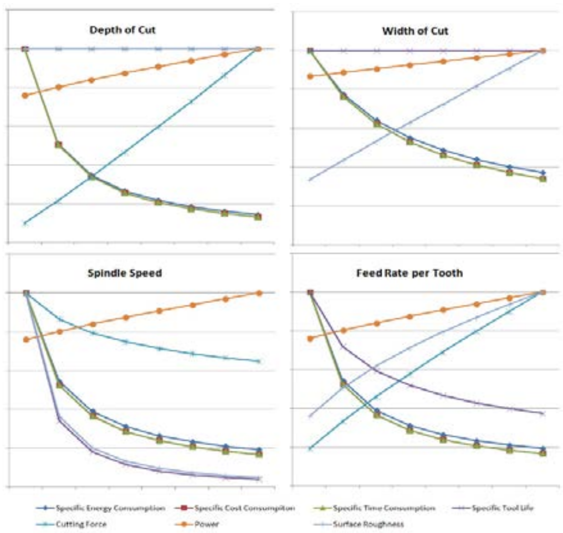

Fig. 2. (a) Variation of various performance measures with cutting conditions

One last aspect of the analysis and characterisation of the factors is the identification that the proportion of energy used to machine is small compared to energy used for auxiliary functions (e.g. to pump coolant). Typical values in the range of cutting condition investigated varied between a minimum of about 1% to a maximum of about 16%, following similar pattern mentioned in the work of Gutowski's team at MIT [1].

2.4 Improvement/Control of performance by optimisation of parameters of current processes, methods and technologies design of new processes, methods and technologies.

Two methods of improving the sustainability performance have been investigated. In the first, parameters of existing processes, methods and technology are optimized to achieve the improvement. One example of this is the optimisation of cutting conditions to obtain reduction in energy consumption.

In the second method, new processes, methods and technologies are designed. Some examples of these new design that have been investigated in our research have included new coolant delivery method such gravity feed, machining in bath of coolant and through tool coolant. Other example include new cutting method/tool design.

2. Adoption of sustainable machining in SMEs in the south of England

This section reports the results of industrial observations and informal interviews conducted with industrial practitioners for the purpose of exploring how sustainable machining could be disseminated to industries. The companies considered include 4 SMEs and 2 Medium to large enterprises. Machine tool and cutting tool manufacturers were also considered though not visited. Over 40 practitioners related to machining were interviewed and these included experienced shop floor practitioners, apprentices, sales managers, line managers, managing directors with machining experience, facility managers and design engineers. Though the interviews and observations were informal and so did not use a formal questionnaire/observation sheet, there were questions designed to direct the informal investigations. These questions were drawn up by being roughly informed by the results of the findings of our research as reported in section 2.

The questions asked are integrated with the results as reported in section 3.1 to 3.3.

3.1 Definition and Measurement of sustainability factors and performance measures

There is awareness of factors involved in machining and their quantitative measures such as depth of cut, spindle speed, feed rate, width of cut, tool parameters (diameter of tool, number of flutes, tool purchase cost), tool wear, surface finish, dimensional accuracy. Factors like cutting force, machining cost are less considered on the shop floor. There is hardly any awareness of energy used in machining as a factor or its importance. The awareness of energy identified related to factory lighting and in one of the instances where the manufacturing process produced high amount of heat and hence some degree of discomfort in summer. There have not been attempt to determine the amount of energy used in machining. The newer CNC machines observed had either a load % or KW reading, but this has not been employed or sometimes not noticed to exist on the machine until it was pointed out during our interviews. In one of the instances, an attempt to request for the interpretation of the load % reading from representatives of machine tool suppliers proved futile after several calls. While results of theoretically predicting energy was found interesting by those interviewed, the response was more of "we believe it when we see it" indicating a preference for a more experiential way of measurement than theoretical prediction. The power measurement device used in our research was demonstrated in 2 of the SMEs, but it was not possible to connect it since the machines were wired directly to the mains and so could not be individually unplugged for measurement purposes.

3.2 Characterisation of factors and performance measures in sustainable machining

There was general awareness on how process parameters affected the performance of machining such as surface finish, stability of cutting (e.g. not resulting in chatter), chip type, temperature at tool-workpiece interface, most of which are experiential, not codified and formalised knowledge. As practitioners were interviewed phrases like "the machine does not like it" was often used. However in this understanding of effects there was not a sense of the relative significance of each of the cutting parameters on the machining performance. Since there is little awareness of machining energy, the influence of the cutting parameters on energy consumption could not be established/raised during the interview. In the industrial observations and interviews some questions were asked to raise some issues of analysis and characterisation of the parameters. In all cases, practitioners, even very experienced and university-level educated ones, were surprised when they were informed that the lighting bulb on the machine tool (especially if it is not an energy efficient bulb) or the coolant pump consumed more energy than the material removal process itself. This is expected since until the results such as reported by Gutowski and his MIT team [1], even the machine tool manufacturers seem not to have noticed this.

3.3 Sustainability Improvement and Control in machining

The issues of how the cutting parameters are determined and hence improved, if need be, are considered here. In most of the cases asked, the determination of cutting parameters were by experience. There were mention of "feeling" and the individual way in which each machinist feels it. A practitioner in training for example, would say he does not go above a certain depth of cut (i.e. knowing which cutting parameter he is comfortable to be able to react to). When pressed more, the practitioners referred to cutting tool manufacturers handbooks as starting points or advice from tool suppliers especially if new materials are machined. Even in these cases the mention of then modifying those parameters to suit the specific machine tool were raised. We could not establish whether some systematic method of experimentation was carried out or whether there was time set apart to carry out formal process improvement, though in one of the instances the practitioners mentioned that there is always improvement and learning and that when tool suppliers suggest improvements, he has to experiment on his own. In one of the SMEs, there was being developed by the lead person on the shop floor, some measure of formal documentation of the parameters including CNC codes to use for different type of tools/material combination. While this standardised the process, it was not clear how empowering it was to the machinists who were to implement it. The large companies observed were noticed to have a practice of outsourcing the generation of the CNC code. In 3 of the 4 SME cases, there was still a large measure of on-machine programming and hardly any extensive use of off-line programming using CAM systems. The 4th SME (which is the case for the longer in-depth study) however used a CAM system run by the planning section and the CNC program implemented on the shop floor was obtained from that section. In this type of case, it is not clear how the interaction between the shop floor staff especially the experienced machinist and the planning department works to arrive at cutting parameters. Though it was noticed that there were input from representative of tool suppliers who even gave advice such as using new toolpath type that was not a feature of the CAM system employed and this advice has been adopted. The role of the representative of tool suppliers shows an example of how improvement were observed to be introduced, including improvement that goes beyond improving process parameters but to design new processes, methods or technology.

3.3.1 Incentive to adopting sustainable machining

One of the problem of considering adoption of energy efficiency seem to be the fact that the financial incentive seem to be low. The energy bill in machine shops as identified by Anderberg [11] as discussions were held with managers, who it seems, knowing their current electricity bill could more sharply see that there was little margin for gain in that direction of improvement.

An energy improvement that seem to have been adopted or in the process of being adopted in the factories is that of factory lighting. One of the SMEs had already adopted energy efficient lighting and another was in the process, having received quote from energy consultants including very detailed return on investment. It seems there were government incentive or subsidy to adopting this type of measure and it appears it is one of the easily reached low hanging fruits on the way to sustainability improvement and even attain ISO 14000 certification.

It was noticed as we discussed with one of the managers, that there was interest when the issue of the possibility of future regulation was brought up. It seem clear to them that while there may not be substantial financial benefit, preparedness for future regulation or demand from customers such as OEM who require their suppliers to align with their sustainability policy as part of their social corporate responsibility reporting may make consideration of energy efficiency of manufacturing processes of interest.

4. In-depth study in an SME

The purpose of the in-depth study is not a study in machining science per se, but a study for identifying important factors that may be required for industries to adopt sustainable machining. Details given are only approximate.

4.1 The case study company and the team involved in the study

The case study company, established over 50 years ago, is a sub-contract precision manufacturing organisation, supplying precision components to customers in sectors such as Aerospace, Defense, Oil & Gas. The factory studied has about 20 CNC machines. The case study was primarily carried out by an employee of the company in the planning department over a period of 6 months. Others involved in the study through giving information and advice included the managing director, heads of the turning and milling sections, CNC machine operators and representatives of a major cutting tool manufacturer.

4.2The case study

The study examined the effect of improving the tool and design and toolpath type on the energy consumption during end milling of Inconel 718. Before choosing to carry out the test on Inconel 718, preliminary tests were carried out on a range of materials employed in the company, namely Delrin, aluminium, carbon steel, stainless steel and Inconel 718. The pre-test were carried out on the slot shown in figure 3 (having a volume of 13.885 cm^3) on a DOOSAN MYNX 750 Machining Centre. Energy measurement was roughly estimated using the load % displayed on the machine tool. This is a very rough approximation and the results shown in figure 4 needs to be interpreted with this in mind. Even with this rough approximation, the specific energy consumptions (SEC) at 0.99, 3.17, 5.63, 4.54 and 7.73 KJ/cm^3 respectively for delrin, aluminium, carbon steel, stainless steel and Inconel 718 respectively, while not exact values, are of the order of magnitude expected when compared to the predicted values shown in the literature where for example for high temperature alloys, values of SEC are indicated to be between 2 and 8.5 kJ/cm^3 [9]. As shown in in figure 4, Inconel 718 (referred to in figure 4 as high temperature alloy) had more indication of offering more possibility for improvement in energy consumed and time taken.

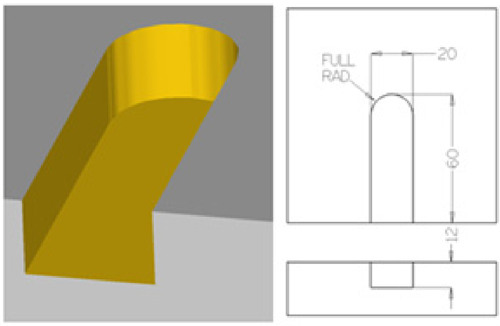

Fig. 3. Slot feature employed for the pre-testing.

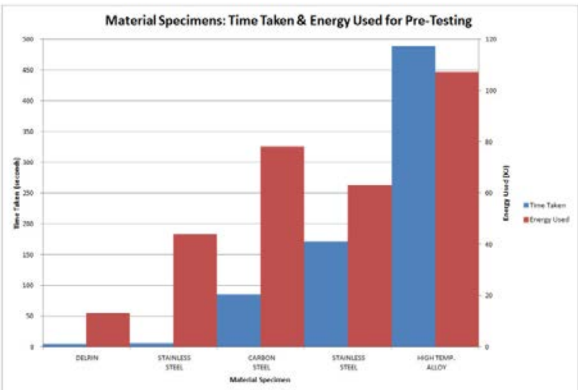

Fig. 4. Time and Energy consumption for different materials.

3 tool design concepts were generated and using an evaluation matrix on various requirements (including cost and versatility to cut several features and potential for improved cutting), one of the tool was selected as the most suitable to be employed for the test and manufactured by the collaborating tool manufacturer. The tool was made in carbide with a coating of Titanium Aluminium Nitride, TiAlN (see figure 5). Using this improved tool design, tests were carried out on features such as profile, slot, counterbore and shoulder. The test used conventional end mills and the improved tool design and toolpath. The results are shown in figures 6 and 7 for time taken and energy consumed.

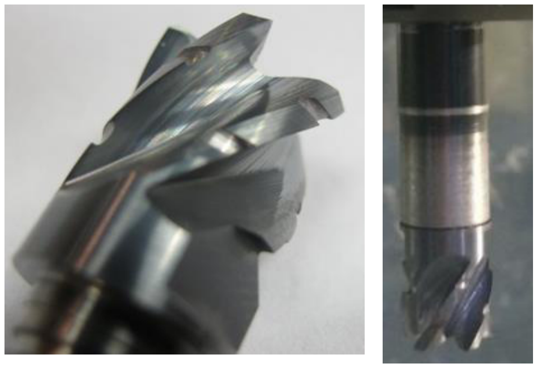

Fig. 5. New tool design.

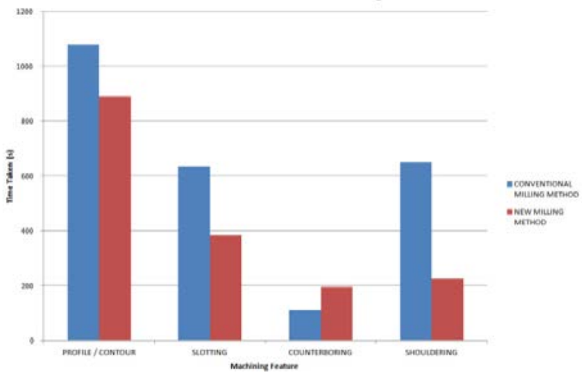

Fig. 6. Time for machining different features using conventional and new tools.

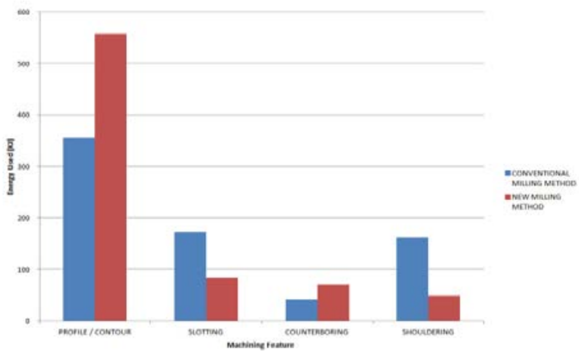

Fig. 7. Energy for machining different features using conventional and new tools.

From figure 6, all other features other than the counterbore had faster processing time. However, the new milling method and tool had improved energy consumption only for machining slot and shoulder features (figure 7). The 2 features with improved processing time and energy consumption were able to employ trochoidal toolpath type, while the others could not. It may be concluded that the improvement were more likely to be due to the toolpath type than to the tool design. The chip formation, however seem to have benefitted from the new tool design as shown in figure 8. Dimensional accuracy and surface finish were also found not to be impaired by the new tool design and toolpath type as they still satisfied typical design requirements.

(a) (b)

Fig.8. (a) Continuous chip formation; (b) Discontinuous chips with new tool.

The estimate of the savings from the energy reduction only showed an amount of about £1000 per annum over the whole shop floor. In contrast, the processing rate is improved to over 150%. Is such savings worthwhile for industries to pursue sustainable machining initiatives?

5. Conclusions

This paper has addressed the subject of identifying factors that could be important in the dissemination of sustainable machining to industries. The following conclusions can be drawn:

- There is some measure of consensus in research on the fact that higher material process rate leads to reduction in specific energy consumption. This means academic research is approaching the point of being ready to be transferred to industry. However, more consensus on the relative significance of various cutting parameters in reducing energy consumptions needs to be reached.

- There is still low awareness of energy at machine or process level but factory level issues such as energy efficient lighting is familiar. Precise measurement of energy on the shopfloor is still problematic.

- Financial gains from reducing energy consumption does not seem enough incentive and only regulative measures, pressure from OEM, customers and governments may result in initiatives for adopting energy efficient machining.

- Adoption may be easier if embedded into existing process improvement methods, most of which currently is driven by tool manufacturers suggestion, especially when new materials are to be machined;

- The conclusions from the in-depth case study seems to indicate that at least in financial terms, the gains are not enough to be an incentive for industries, though the promise of higher production rate may be an attraction. The gains may be more in better use of advanced manufacturing technology, better resource accounting (which just happens to include energy consumption) or general empowering of shop floor staff. The role of technology providers such as tool manufacturers was identified.

- Future research needs to look at how to achieve more consensus on the academic research that is to be transferred to industry. More formal industrial studies need to be carried out and a more systematic approach is required for improvements such as tool design so that influence of factors can be better identified.

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